IAC-06-B6.3.03

OVERVIEW OF RECENT ENHANCEMENTS TO THE BUMPER-II METEOROID & ORBITAL DEBRIS RISK ASSESSMENT TOOL

Mr. James L. Hyde
Barrios Technology, United States, james.l.hyde@nasa.gov

Dr. Eric L. Christiansen
NASA/Johnson Space Center, United States, eric.l.christiansen@nasa.gov

Mr. Dana M. Lear
ERC, United States, dana.m.lear@nasa.gov

Mr. Thomas G. Prior
Hamilton Sundstrand, United States, thomas.g.prior@nasa.gov

ABSTRACT

Discussion includes recent enhancements to the BUMPER-II program and input files in support of Shuttle Return to Flight. Improvements to the mesh definitions of the finite element input model will be presented. A BUMPER-II analysis process that was used to estimate statistical uncertainty is introduced.

INTRODUCTION

BUMPER-II is an MMOD risk analysis program originally developed by for the Space Station Freedom Program. Over the years, the capabilities of this engineering analysis tool have been extended to include the Space Shuttle Orbiter, the International Space Station (ISS) and many other spacecraft. When provided with a vehicle shape, orbit parameters and applicable ballistic limit equations with defined failure criteria, the BUMPER-II code will calculate the MMOD risk for spacecraft in low Earth orbit against a variety of natural and man-made environments. Thousands of hypervelocity impact tests have been performed on representative samples of ISS shields and subsystems, Shuttle thermal protection system (TPS) materials [1], Extravehicular Mobility Unit (EMU) materials [2] and other spacecraft components to determine MMOD impact parameters at the failure limits of the various subsystems. BUMPER is used to calculate MMOD impact risks to specific Orbiter surfaces. An integrated mission assessment is completed using Poisson statistics and knowledge of the distribution of times spent in each unique Orbiter attitude [3].

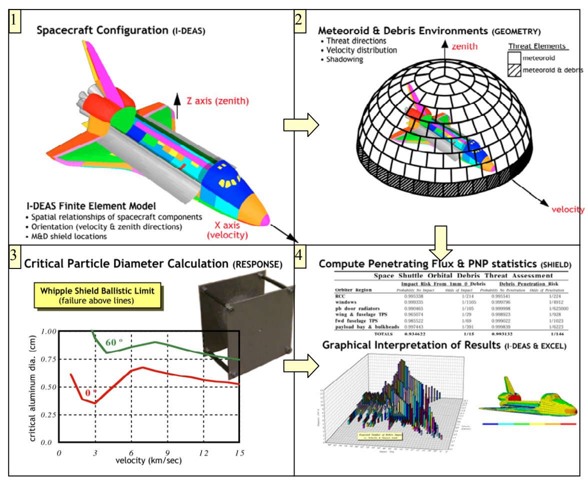

Fig. 1: BUMPER-II functional overview.

FAILURE CRITERIA UPDATES

As part of the Shuttle Return-to-Flight effort, the NASA Johnson Space Center's Hypervelocity Impact Technology Facility performed hypervelocity impact testing and analysis of Shuttle wing leading-edge (WLE) reinforced carbon-carbon (RCC) test samples to update WLE threshold failure criteria [4]. After the hypervelocity impact tests, the samples were exposed to typical reentry heating conditions at the NASA JSC Arc-Jet (AJ) Facility to determine the extent of heating induced damage growth.

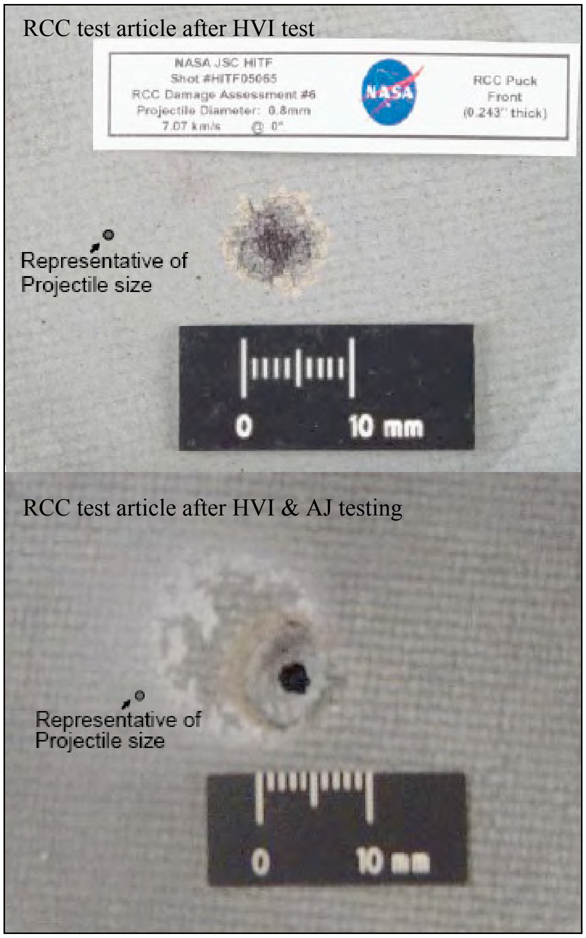

Fig. 2: 0.8 mm aluminum HVI/AJ RCC test results.

It was found from the HVI/AJ testing that non-penetrating pits would lead to burn-through in some areas of the WLE where burn-through can lead to loss-of-vehicle (LOV) during reentry.

Figure 2 shows the resulting damage caused by a 0.8 mm diameter aluminum hypervelocity impactor and subsequent damage growth due to AJ testing. For STS-107 and previous missions, WLE failure threshold consisted of 1 inch diameter allowable hole sizes in RCC on the upper surface and ¼ in. hole size on the lower surface. The results of the recent RCC/AJ testing indicated that the WLE failure criteria for LOV should be reduced for MMOD assessments on future missions. Figures 3 and 4 show the WLE and nose failure criteria maps before and after the recent changes. The reduction in allowable damage results in increased calculated MMOD risks for future missions [5].

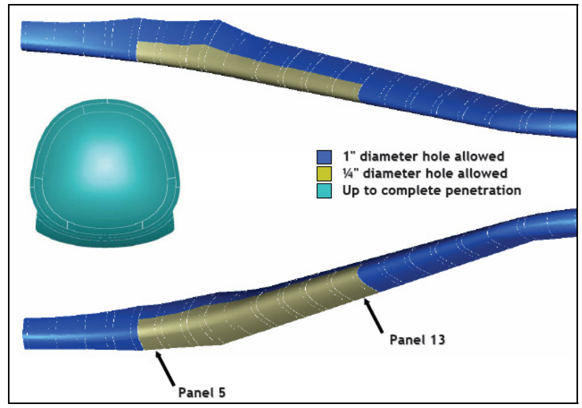

Fig. 3: Pre-STS-107 RCC Failure Criteria Map.

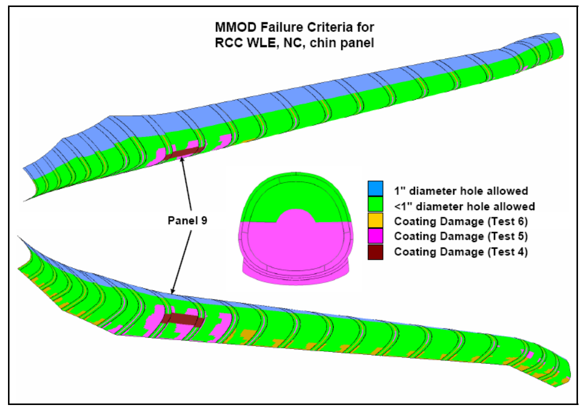

Fig. 4: Post-STS-107 RCC Failure Criteria Map.

ORBITER/ISS MATED ATTITUDES

The Shuttle and International Space Station (ISS) Programs have decreased MMOD impact risks to the orbiter by changing the orientation of the ISS while the shuttle is docked. The change in orientation – essentially flying the ISS "backwards" – provided incidental shielding to the shuttle as well as directing MMOD sensitive areas of the WLE and nose cap away from the majority of the MMOD particle flux. Figure 5 shows the shuttle-ISS docked orientation change with respect to the ISS velocity direction. In previous ISS missions, the belly of the vehicle typically faced into the velocity direction of ISS motion and highest MMOD impact flux. The attitude change orients the bottom of the shuttle in the wake direction of ISS reducing MMOD impacts to the most vulnerable surfaces of the vehicle and improving crew safety and odds of mission success.

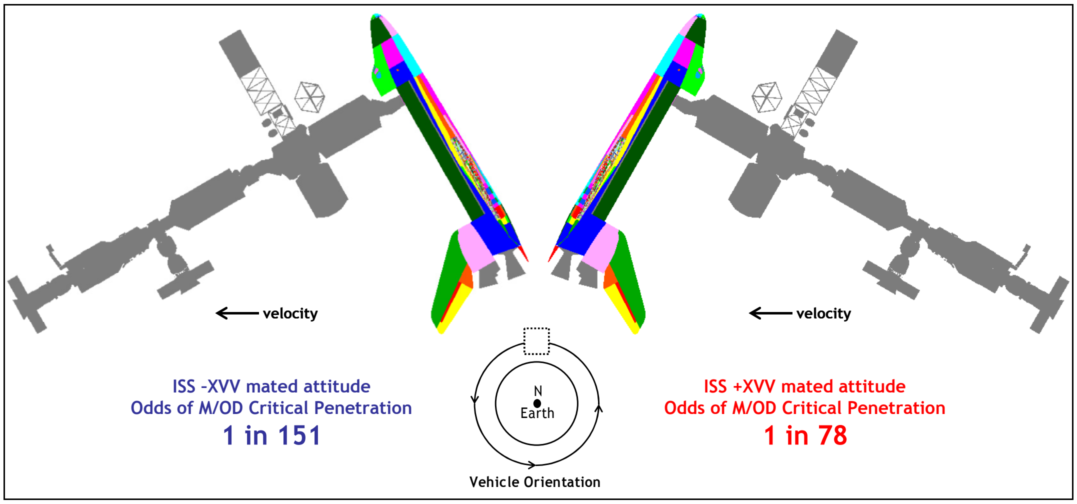

Fig. 5: Shuttle-ISS mated attitudes before STS-107 (ISS +XVV) & after STS-107 (ISS -XVV).

A trade study was performed to assess the quantitative effect of the ISS -XVV attitude change on the critical MMOD risk for the STS-114 mission. The results of the mated attitude trade study are illustrated in figure 5. The ISS -XVV mated attitude used for STS-114 increased the odds of MMOD critical penetration from “1 in 78” to “1 in 151”, an overall mission risk reduction of nearly 2X. The bar chart in figure 6 illustrates the qualitative effect of orbiter attitude on MMOD critical penetration risk using the RCC failure criteria shown in figure 4.

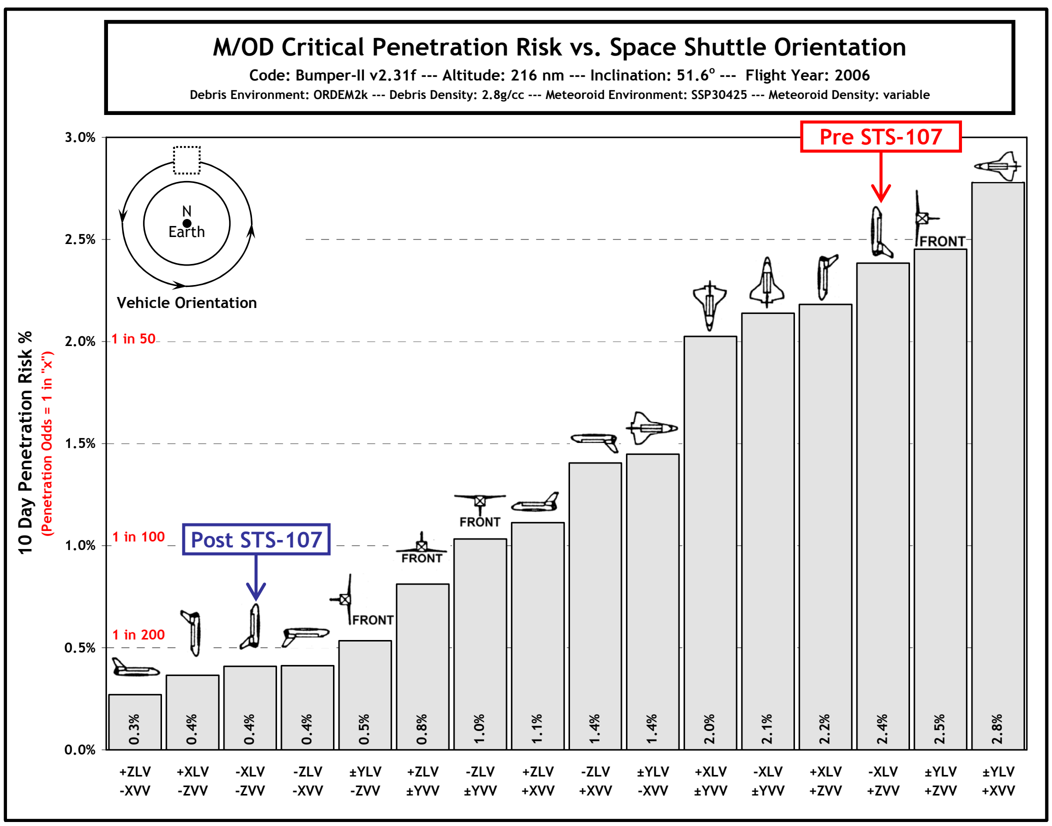

Fig. 6: Critical MMOD risk as a function of orbiter attitude.

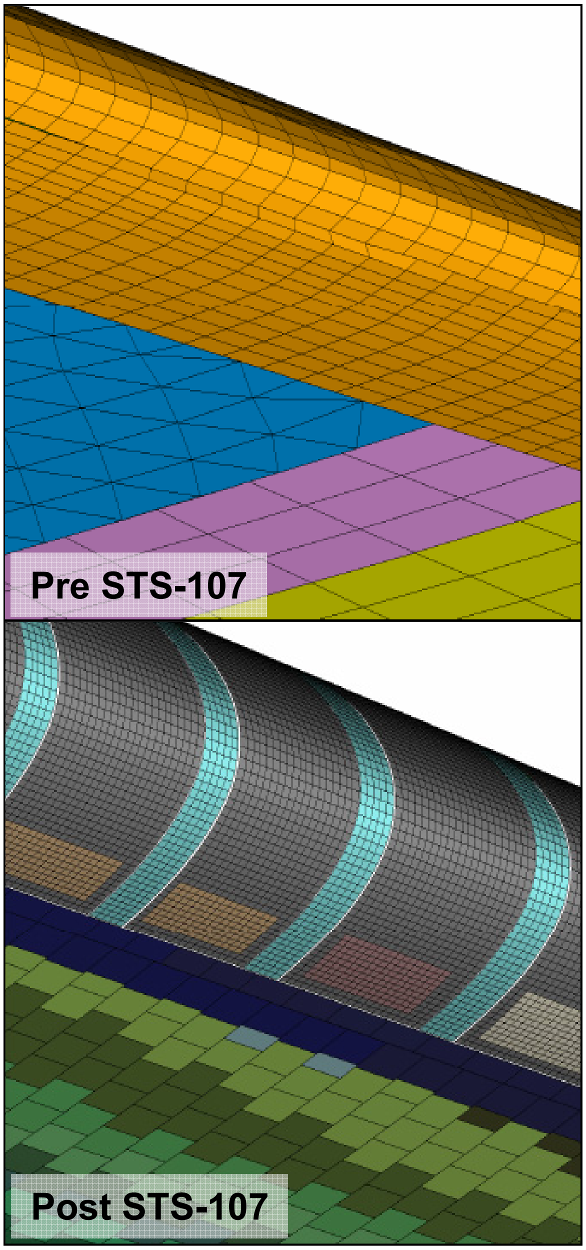

Fig. 7: WLE RCC finite element mesh.

ORBITER FEM UPDATES

Figure 7 shows a detail of the WLE RCC area of the orbiter that is represented by a detailed finite element mesh containing over 50,000 elements. Each color change represents a different failure criteria region. This mesh area has 592 distinct regions, where hypervelocity impact damage resistance is defined to reflect failure criteria and physical differences such as location, thickness, and material. [6]

The Nose Cap/Chin Panel area of the orbiter was also revised and is now composed of nearly 5000 elements. These newly revised mesh areas provide a significant increase in analytical detail, allowing property definition and risk calculations for specific regions of individual WLE components such as panels and seals. Figure 8 depicts the new finite element mesh in the nose cap/chin panel region of the Shuttle.

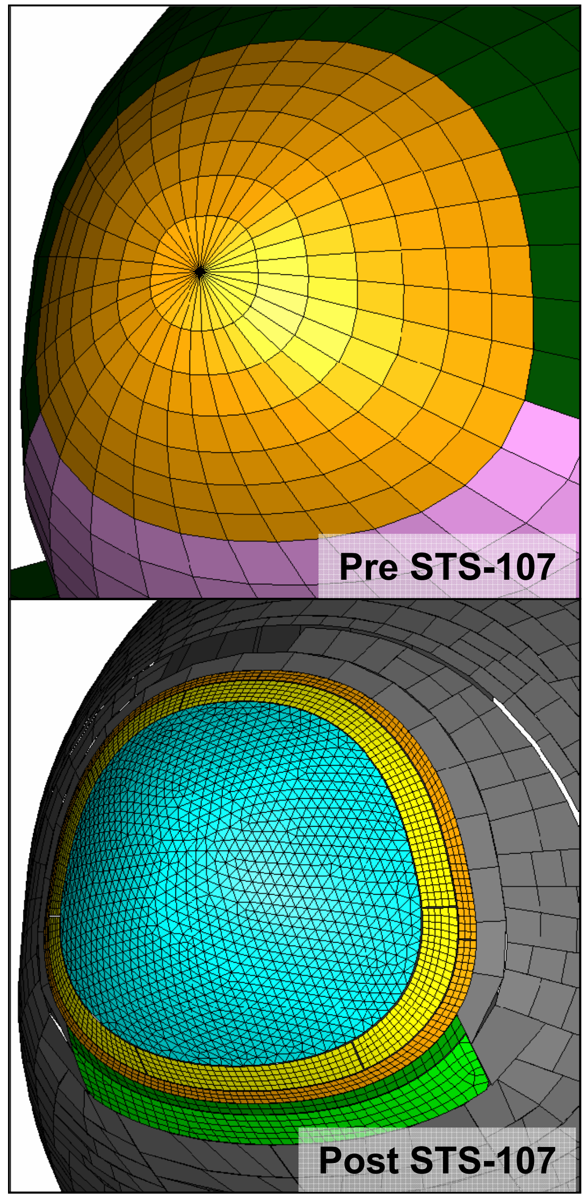

Fig. 8: Nose cap/chin panel finite element mesh.

ESTIMATION OF UNCERTAINTY BOUNDS

This section documents a proposed technique to estimate uncertainty bounds in BUMPER-II assessments of MMOD risk to the shuttle. A typical analysis is comprised of input scripts and data files for the Bumper program modules (Geometry, Response & Shield) that describe the input parameters for the mission. This architecture allows for multiple analysis cases to set up in a script through loop constructs. [7]

Methodology

The BUMPER-II code calculates an expected number of penetrations of a spacecraft based on a single set of program inputs. To estimate uncertainty bounds, multiple instances of the same calculation need to be run while varying selected environment and penetration input parameters. The "environment" variables for this study were MMOD flux and density, OD velocity distribution. Ballistic limit equations and failure criteria were selected as the "penetration" variables. Figure 9 provides an outline of the risk assessment methodology used in this assessment. The upper "BUMPER Input" boxes describe the input phase for the analysis; the intermediate boxes indicate calculations and the lower box represents output processing.

The first step in the analysis is the statistical modeling of selected input parameters. The input distribution definitions are used as directives to an external (i.e., not part of the Bumper code) statistical processor that generates randomly selected values of Bumper input parameters. The input parameter set is then copied into a BUMPER-II input file which runs the code once

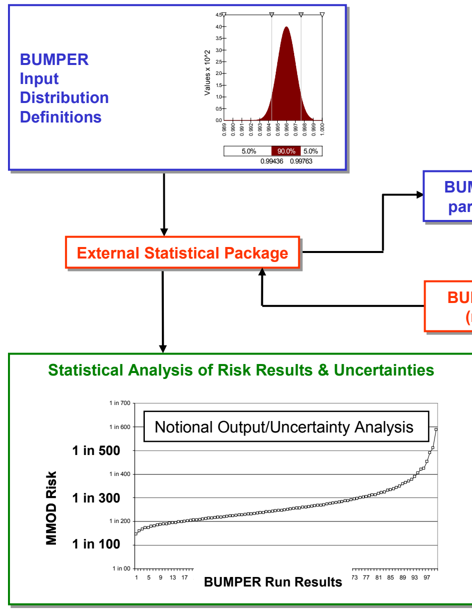

Fig. 9: Risk assessment workflow.

for each case in the parameter set. MMOD risk output values from the runs is tabulated and sent back to the statistics processor, where uncertainty bounds can be determined. The technique used in this analysis for the estimation of uncertainty bounds incorporates Bumper code input variables from the sensitivity analysis with the added complexity of allowing values in between the upper and lower bounds. Input distribution types chosen for each variable are provided in table 1.

Probability Distribution Functions (PDF)

A "discrete" distribution selects from a defined set of inputs while a "continuous" distribution can return any value between the limits. The uncertainty analysis uses a statistical preprocessor (@Risk v4.5) to select values for

Type	Name	Distribution Type	PDF	Limit Values	
Environment	OD Flux	Continuous	Log Normal, μ=1.0	0.9	1.6
Environment	MM Flux	Continuous	Log Normal, μ=1.0	0.5	2.0
Environment	OD Velocity	Discrete	---	Min, Base, Max	
Environment	OD Density	Continuous	Log Normal, μ=2.8	1.0	7.9
Environment	MM Denisty	Continuous	Log Normal, μ=1.0	0.5	1.9
Penetration	MM/OD BLE	Continuous	Extreme Value, μ=1.0	0.9	1.15
Penetration	MMOD Failure Criteria	Discrete	---	Min, Base, Max	

Table 1: Input distribution types.

each of the Bumper inputs using the probability distribution functions (PDF) discussed below. The Log-normal PDF for OD and MM flux input are the only PDF's with uncertainty values of 68% (±1 sigma) at the distribution limits.

The other continuous distributions in this assessment were assumed to have 95% confidence bounds between parameter value extrema. MM and OD density Log Normal input distributions were modeled with 95% confidence bounds at the extrema and the mean set to the baseline analysis value (OD density = 2.8 g/cc and MM density = 1.0 g/cc).

The discrete PDF for the OD velocity distribution was set to select the nominal ORDEM2000 orbital debris velocity distribution option twice as often as the equally likely minimum and maximum velocity distribution options.

The Penetration PDF's used in the uncertainty analysis are correlated to shield penetration, so they were not modeled as separate distributions for meteoroids and orbital debris. An Extreme Value PDF was used to model the Ballistic Limit Equation (BLE) factor inputs, with a mean at the nominal analysis baseline of 1.0 and ~95% of the area between the analysis extrema of 0.9 and 1.15. Three discrete options are modeled for failure criteria. The "max" and "min" options were assumed to be half as likely to occur as the "nominal" option.

<u>Assessment Parameters</u>

The following constants were used for the uncertainty calculations in BUMPER-II:

OD Environment	– ORDEM 2000
MM Environment	– SSP-30425, Rev. B
Year	– 2003
Inclination	– 51.6°
Altitude	– 400km

<u>Unmated</u>

Attitude	– RPY = 0°, 180°, 0°
Exposure Time	– 3.125 days (29%)

<u>Mated</u>

Attitude	– RPY = 0°, 113°, 0°
Exposure Time	– 7.625 days (71%)

Figure 10 depicts the two finite element models that were used for the uncertainty assessment.

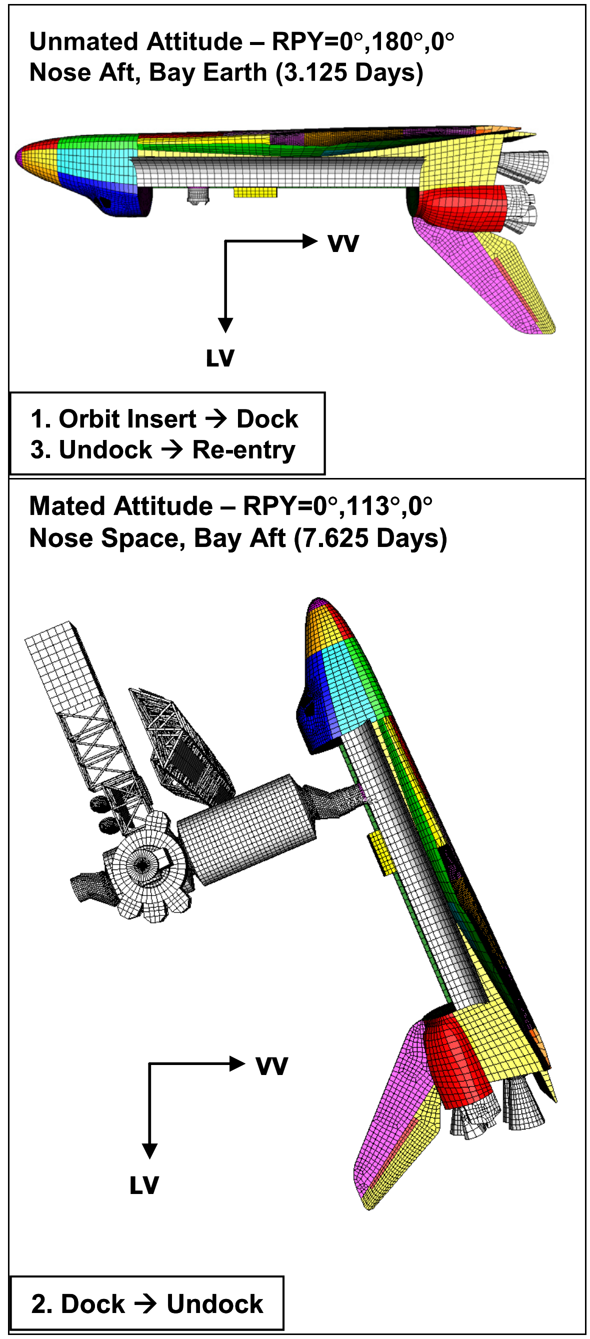

Fig. 10: BUMPER-II finite element models.

<u>Analysis Results</u>

Figure 11 shows the frequency plot of the MMOD critical risk output for the 180 cases in this analysis. Using @Risk, a probability distribution was fitted the output values. Figure 12 shows the 90% uncertainty bounds on the example baseline analysis of 1 in 440 vary from a minimum of "1 in 114" to "1 in 2654".

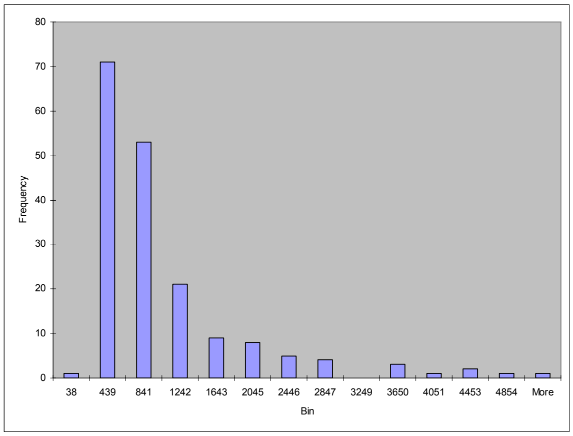

Fig. 11: MMOD risk frequency plot.

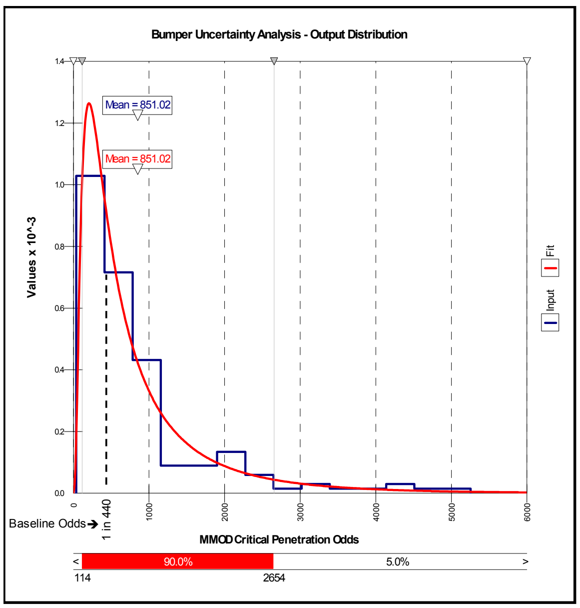

Fig. 12: MMOD risk distribution.

Forward Work

The next version of the uncertainty analysis will support the updates to the orbiter finite element model documented in this paper. The failure criteria changes to the RCC wing leading edge and the nose cap areas significantly effects MMOD risk. Forward work includes updating the uncertainty assessment based on the new failure criteria as well as reflecting the latest changes in uncertainty ranges of key risk assessment parameters Additional research into the parameters used in the input PDF's may also be desirable.

REFERENCES

1. Christiansen E.L. and Friesen L.J., "Penetration Equations for Thermal Protection Materials", Int. Journal Impact Engineering, Volume 20, 1997.

2. Christiansen E.L. Cour-Palais B.G. and Friesen L.J., "Extravehicular Activity Suit Penetration Resistance", Int. Journal Impact Engineering, Volume 23, 1999.

3. Hyde J.L. and Christiansen E.L., "Space Shuttle Meteoroid & Orbital Debris Threat Assessment Handbook: Using the BUMPER-II Code for Shuttle Analysis", JSC-29581, December 2001.

4. Lyons F., "RCC Hypervelocity Impact Testing for MMOD Impact Assessment Part 1, Return to Flight", JSC-62926, March 2005.

5. Lyons F., "RCC Hypervelocity Impact Testing for MMOD Impact Assessment Part 2, STS-114 Flight Readiness Review", JSC-62988, May 2005.

6. Lear D., et al., "Enhancement of Space Shuttle Models Used in BUMPER Micrometeoroid and Orbital Debris Risk Analyses", Orbital Debris Quarterly News, Volume 9 Issue 2, April 2005.

7. Hyde J.L. and Christiansen E.L., "Bumper-II Meteoroid and Orbital Debris Threat Assessment Code: Sensitivity Analysis & Uncertainty Bounds", JSC-63313, September 2005.